論文の内容の要旨

Wall Thermal/Chemical Effects on Premixed Flame in Micro Channels
(マイクロ流路内予混合火炎における熱・化学的壁面効果に関する研究)

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1. Introduction

Portable power source with higher energy density has been the initial target of intense investigations on micro combustors. Recent studies on combustion phenomena in micro scale lead to the findings that both wall thermal and chemical boundary conditions play important roles in flame behaviors.

Miesse et al. [1] and Kim et al. [2] investigated the effect of wall material/surface property on quenching distance in parallel plates with external heating. They found that inert material and surface are effective against chemical quenching, and chemical quenching instead of thermal quenching dominates for high wall temperature. However, there are several suspicious issues in their measurements. (1) Bulk material is used, and the wall temperature is not directly measured. (2) The wall surface of their sample plates is rough. Radicals are likely to diffuse into the valleys on the surface, thus the combustion process can be changed by the radical destructions. (3) The thermal conductivity of their sample plates is different for different wall materials, thus the wall thermal condition is changed when wall materials are different.

Several research efforts [1, 3] have been made on flame behavior in millimeter-scale tubes/channels. An interesting phenomenon, flame oscillation, is observed, which is a periodic process of flame ignition and quenching. However, most of the previous investigations are phenomenological, and are carried out in a limited parameter space. The lack of optical access in opaque burners and the curvature of tube burners make the optical measurements of the flame difficult. Systematic investigation with more quantitative information of the flame shall provide more profound discussions.

The present study provides experimental investigations of wall thermal and chemical effects on steady and oscillating flames in micro channels. Major contents include quenching distance measurement for the investigation of wall thermal and chemical effects, systematic investigation of flame behavior in micro channels, and time-resolved/phase-locked optical measurements of oscillating flame.

2. Quenching distance in parallel plates

To examine the wall chemical effects, quenching distance is measured with flame in parallel quartz plates coated with ~100nm-thick metallic films. By doing so, (1) wall chemical effects can be checked without changing the thermal wall boundary condition; (2) both the quartz plate and metallic coated plate have very smooth surface, so that the combustion process is not changed by the surface roughness. The plates are externally heated with IR lamp heaters. The wall temperature is monitored by thermocouple plugged in the plate, and carefully controlled. The measurement point is only 1mm away from the test surface to minimize the difference from exact surface temperature.

The quenching distance measured for quartz plates decreases with increasing wall temperature, which agrees with the conventional thermal theory, and quantitatively agrees well with results of Miesse et al., showing that the thermal effect is dominant. On the other hand, quenching distance for metallic surface is slightly larger than that for quartz plates, but also decreases with increasing wall temperature. Therefore, weak chemical effect exists for both low and high wall temperature, but thermal effect is dominant in the temperature range investigated. It has been demonstrated that flame can propagate into 0.6 mm gap, and it is still possible in thinner channels as long as the wall heat loss is compensated.

3. Flame in micro combustors

Based on the quenching distance results in parallel plates, quartz is chosen as the construction material of micro combustors. Plannar quartz combustors having channel heights of 0.7/1.0/1.5 mm have been developed for quantitative investigations of steady and oscillating flames. The present combustor enables optical access for the investigation of quenching mechanisms in micro channels with laser imaging techniques. Microscale steady and oscillating flames are confirmed through CH*/OH* chemiluminescence. Premixed CH_4/air flame is established in the combustion chamber by precise control of heat input to the wall, and is examined for channel height of 0.7, 1.0 and 1.5 mm.

Both steady flame and oscillating flame are observed, and the oscillating flame is in the fuel-rich side of the extinction limits map. Oscillating flame ignites at the exit where the fuel/air mixture is diluted by the surrounding air into a flammable concentration. There is a narrow quenching region between the steady flame and oscillating flame regions, where strong hysteresis exists due to the heat transfer from the flame to the wall. It has been found that the extinction limits region becomes narrower for thinner channel, and broader for higher wall temperature, which shows the wall thermal effect. Quenching distance is dependant on the wall temperature, and can be smaller than 0.7 mm for wall temperature over 800°C in planar quartz channels, which shows good agreement with the measurement in parallel plate configuration. Flame structure in the micro combustor is investigated with scanning micro OH-PLIF imaging techniques. OH-PLIF images of micro flame show a concave-shape flame front, which is the result of the non-uniformity of wall-temperature distribution. Flame temperature is measured with SiO_2-coated thermocouple, and higher flame temperature is found for higher wall temperature. OH 2-line PLIF method for measurement of flame temperature is applied to the steady flame, and the result agrees well with the thermocouple measurement.

4. Flame oscillation

Detailed process of flame oscillation is captured with time-resolved chemiluminescence imaging technique. Chemiluminescence images of an oscillating flame reveal that this is a periodic process of flame ignition at the exit, and propagation upstream, and then quenching due to heat loss to the wall, and finally recharge to the exit for the start of another cycle. A phenomenological formula has been derived for the estimation of oscillation frequency. Oscillation frequency measured in the present experiment is in the range of 30-500 Hz. The oscillation frequency is then investigated over the parameter space of wall temperature, mixture velocity and channel height. The experiment results are explained well by the formula. One emphasis of this part is on the reasoning of flame quenching by gradual heat loss from the flame to adjacent wall during the propagation. Phase-locked OH-PLIF has been developed for 3-D structure of the flame, and flame temperature measurement with the 2-line method. The flame quenches first near the sidewall where temperature is lower. The propagation becomes slower as the flame moves closer to the quenching position, as shown by both the time-resolved chemiluminescence and phase-locked OH-PLIF images. The thermal quenching hypothesis is supported by phase-locked OH 2-line PLIF measurement showing the gradual decrease of flame temperature and analysis of time resolved OH* chemiluminescence images showing the decrease of transient propagating velocity. Finally, flame instabilities associated with premixed flames in the micro combustor have been covered.

5. Conclusions

Quenching distance measurement for different surface material under well-defined wall boundary conditions has been conducted in the configuration of flame in parallel plates. The inert surface gives slightly smaller quenching distance than the metallic surface for both low and high wall temperature, where weak chemical effect exists. Quenching distance for both the inert surface and metallic surface decreases with the increase of wall temperature, showing that the thermal effect. It is concluded in the present study that, unlike the claims of dominant chemical effect for high wall temperature made by Miesse et al. and Kim et al., thermal effect is the overall dominant factor within the wall temperature range and length scale investigated.

Micro quartz combustors with channel height of 0.7/1.0/1.5 mm have been developed for quantitative optical measurements of steady and oscillating flames with Time-resolved chemiluminescence and phase-locked two-line LIF measurement systems. The measurements provide quantitative information of the flame such as the flame temperature, flame speed and flame structure, which are not well discussed previously [1, 3]. The flame temperature, flame speed, flame structure, extinction limits region and flame stability are found greatly affected by the wall temperature. Flame temperature is increased by increasing the wall temperature. Thus, the extinction limits region becomes broader, and quenching distance can be smaller. The quenching distance for the quartz channel can be smaller than 0.7 mm when the wall temperature is over 800 ºC. The extinction limits region becomes narrower with a thinner channel due to stronger wall effect.

Oscillating flame, of which frequency is in the range of 30-500Hz, is found mainly distributed in the fuel-rich side in the flammability map. There is a small quenching area between the steady flame and oscillating flame regions, which is due to strong hysteresis due to the thermal coupling between the flame and the wall. Oscillating flame is a periodic process of flame ignition at the exit, and propagation upstream, and then quenching by heat loss to the wall, and finally recharge to the exit for the next ignition. The oscillation frequency can be analyzed with a phenomenological formula considering the thermal effect. It is noted that the quenching of an oscillating flame is caused by the heat loss to the wall, as also pointed out in previous studies [3]. The present investigation supported the hypothesis by quantitative measurements showing the decrease of flame temperature during propagation and the deceleration of flame propagation.

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[2] K.T. Kim, D. H. Lee, and S. Kwon, Effects of thermal and chemical surface-flame interaction on flame quenching, *Combust. Flame*, Vol. 146, pp. 19-28, 2006.

[3] K. Maruta, J.K. Parc, K.C. Oh, T. Fujimori, S.S. Minaev, and R.V. Fursenko, Characteristics of microscale combustion in a narrow heated channel, *Combustion, Explosion, and Shock Waves*, Vol. 40, pp. 516-523, 2004.